STOCHASTIC-BASED COORDINATED TRADING OF COMBINED CYCLE & WIND UNITS

BY

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بسم الله الرحمن الرحيم

DEDICATED TO

My Beloved Parents

My Beloved Wife

And

My Beloved daughters Manal and Sara

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قال تعالى

بسم الله الرحمن الرحيم

﴿وَالضُّحَى ﴿١﴾ وَاللَّيْلِ إِذَا سَجَى ﴿٢﴾ مَا وَدَّعَكَ رَبُّكَ وَمَا قَلَى ﴿٣﴾ وَلَلْآخِرَةُ خَيْرٌ لَكَ مِنَ الْأُولَى ﴿٤﴾ وَلَسَوْفَ
يُعْطِيكَ رَبُّكَ فَتَرْضَى ﴿٥﴾ أَلَمْ يَجِدْكَ يَتِيمًا فَآوَى ﴿٦﴾ وَوَجَدَكَ ضَالًّا فَهَدَى ﴿٧﴾ وَوَجَدَكَ عَائِلًا فَأَغْنَى ﴿٨﴾ فَأَمَّا الْيَتِيمَ فَلَا
تَقْهَرْ ﴿٩﴾ وَأَمَّا السَّائِلَ فَلَا تَنْهَرْ ﴿١٠﴾ وَأَمَّا بِنِعْمَةِ رَبِّكَ فَحَدِّثْ. ﴿١١﴾﴾

All praise is due to **Allah**, the lord and sustainer of the worlds, for His countless favors and seeing me this far in life. Then, I appreciate the support and prayers of my **parents**, all through my life and especially during this work. To my siblings, I say thank you all for being there for me.

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THESIS ABSTRACT (ENGLISH)

Name	[Fahmi Saeed Baroishad]
Title	[Stochastic-based Coordinated Trading of Combined Cycle & Wind Units]
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Trading of Combined Cycle Units (CCU) energy in short-term electricity markets is complicated since CCU operates with multiple configurations based on the number and the status of combustion turbines and steam turbines. However, CCU has distinct advantages like high efficiency, faster response, shorter installation time and environmental friendliness than the simple cycle (thermal unit). Therefore, combined cycle unit is suitable to coordinate with the wind energy due to wind bidding risks. Consequently, bidding wind energy during short-term has uncertainties like hourly available wind, energy prices, and imbalance penalties which could affect the electricity market as a high risks. In this thesis, the coordination between wind and combined cycle units is proposed for the day-ahead energy market bidding. For CCU, a component model is used. The problem is formulated as a mixed integer linear programming (MILP) problem that determines the optimal bidding curves for combined cycle and wind units. Also it determines the unit commitment of combined cycle.

Stochastic programming (SP) is used in order to account for uncertainties associated with wind power output, spot market energy price, and imbalance up/down price. The main objective is to determine the optimal trade-off bidding strategy that maximizes the total expected profits. This study takes into account the various constraints of combined cycle units such as minimum on/off time, ramping rates, minimum and maximum power outputs, and startup costs. A simulation study for a producer with combined cycle and wind units is carried out to demonstrate the benefits of coordination. The influence of risk control by using the conditional value at risk (CVaR) on the coordinated case is also considered.

THESIS ABSTRACT (ARABIC)

الأسم الكامل : فهمي سعيد برويشد

عنوان الرسالة: تجارة توافق الطاقة من الوحدة المركبة ووحدة الرياح اعتمادا على البرمجة العشوائية .

الدرجة العلمية : ماجستير العلوم

مجال التخصص الرئيسي: الهندسة الكهربائية

تاريخ الحصول علي الدرجة: أكتوبر 2014

تجارة طاقة الوحدة ذات الدورة المدمجة (المركبة) خلال المدى القصير يعتبر معقد بسبب أن الوحدة ذات الدورة المدمجة تعمل على أشكال متعددة اعتمادا على عدد و حالة التوربينات الاحتراقية والتوربينات البخارية. الوحدة ذات الدورة المدمجة من ناحية اخرى تمتلك مزايا واضحة مثل الكفاءه العالية، الاستجابة السريعة، قصر وقت التثبيت و الملائمة البيئية مقارنة بالوحدة ذات الدوة البسيطة (الوحدة الحرارية). لذلك الوحدة ذات الدورة المدمجة ملائمة للتوافق مع طاقة الرياح من اجل المخاطر التي تتعرض لها تجارة طاقة الرياح. بناءا على ذلك تجارة طاقة الرياح خلال المدى القصير تمتلك اضطرابات مثل وفرة الرياح كل ساعه، اسعار الطاقه و غرامات عدم الاتزان الانتاجي التي تؤثر على سوق الطاقة باعتبارها مخاطر عالية. هذه الاطروحة تعرض التوافق بين وحدة الرياح و وحده الدورة المدمجة. وحدة الدورة المدمجة ذات النموذج الفيزيائي استخدمت في هذه الدراسه. المسألة صيغت على انها مسألة برمجه خطية مدمجة تحسب أفضل محاور تجارة توافق طاقة وحدة الرياح والوحده المركبة مع حساب جدولة الحالة التشغيلية للوحدة ذات الدورة المدمجة.

البرمجة العشوائية ماخوذة في الاعتبار نظرا لوجود المتغيرات المضطربة (مثل طاقة الرياح، اسعار الطاقه المتداولة و غرامات عدم الاتزان الانتاجي الدنياء والعليا). الهدف الرئيسي هو حساب أفضل استراجية لتجارة مزود الطاقه التي تزيد الارباح الكلية المتوقعة. هذه الدراسة أخذت في الاعتبار القيود المختلفه لوحدة التوربينات الغازيه ذات الدورة المدمجة مثل اقل واكثر وقت لتشغيل الوحدة، اقل واكثر كميه من الطاقة يمكن ان تزيد بها الوحده خلال

فترة محددة، اقل و اعلى كمية من الطاقة يمكن انتاجها و تكاليف بداية تشغيل الوحدة. محاكاة هذه الدراسه لمنتج يمتلك الطاقة التوافقية من الرياح و الوحدة ذات الدورة المدمجة تم تنفيذها لدراسة فوائد عملية التوافق الانتاجيه للوحدتين. أيضا تم أخذ في الاعتبار تاثيرالتحكم بالمخاطر باستخدام عامل تحكمي يدعى (CVaR) على تجارة توافق الوحدتين.

CHAPTER1 INTRODUCTION

1.1 BACKGROUND

Wind plants have become wide spread in the last two decades due to their competitive advantages of zero fuel cost and environment friendliness compared with traditional energy sources. Current global growth of wind power has reached 300GW by mid of 2014. More specifically, in China, U.S, Germany and Spain, the expansion of wind power reached to 98GW, 61.9GW, 36GW and 22.9GW, respectively, by the middle of 2014 [1]. The future expectations are about 500GW by the end of 2015 and about 1000GW by the end of 2020 [2]. Wind power is an intermittent and uncertain source of electric energy due to its dependence on varying wind conditions. Thus, the participation of wind power in electricity market poses new challenges for both system operator and energy producer in terms of maintaining system security and ensuring a profitable business, respectively.

In pool-based electricity markets, there is a high demand for renewable resources, such as wind which contributes to the increase in the profits of generation companies (GENCOs) [3]. However, the intermittency and unpredictability of wind power output creates difficulty in control of frequency and scheduling. As a consequence, bidding wind energy in short-term markets is risky because of the uncertainties in hourly available wind, energy prices, and imbalance penalties. Thus, integrating wind power with controllable sources, like combined cycle unit is recommended to reduce bidding risks and, consequently, increase profits of the GENCO.

To deal with the variability and uncertainty of wind energy, researchers have made use of different techniques to mitigate the risks in wind energy trading. The works in [4] and [5] deal with coordination of wind and hydro units along with a comparison between coordinated and uncoordinated trading strategies. Coordination between wind and other storage media has been presented in [6]. A detailed research has been carried out in [7], where the trading of wind energy is discussed considering uncertainties such as wind output, energy spot market prices, and imbalance penalties. The objective is maximizing wind trading profits while controlling its risks via maximizing the control metric called conditional value at risk (CVaR) is observed. Stochastic programming is used.

Coordinated bidding of wind plants and thermal units as a risk control strategy has been presented in [8]. The objective is to maximize the expected profits while managing the risks associated with periods of high wind imbalance or low wind/thermal revenues. The CVaR is used as a risk management metric and stochastic programming is applied.

Combined Cycle Units (CCUs) are considered as one of most reliable sources that have the ability to operate under flexible conditions responding to market volatilities [9]. CCUs have higher efficiency, reaching up to 60%, compared with simple cycle thermal unit. The higher efficiency is achieved by capturing the waste heat from the gas turbine exhausts into a heat recovery steam generator (HRSG) and using it to produce superheated steam that drives a steam turbine [10].

This work is based on a combined cycle component (CCC) model. A stochastic mixed-integer linear programming (MILP) model is developed for a combined cycle component bidding to determine the expected profits. In addition, various constraints for a combined cycle unit such as minimum up/down time, ramping rates, minimum and maximum power outputs, and startup costs are taken in account. Then, coordinated bidding between combined cycle unit and wind is carried out for a day-ahead electricity market to maximize the expected profits. Stochastic programming (SP) [8],[11],[12],[13] has been used in this work to deal with the uncertainties variables. The CVaR is used also to mitigate the bidding risks.

1.2 MOTIVATION AND PROBLEM DESCRIPTION

The integration of wind energy is increasing rapidly in several power systems throughout the world [1] and [2]. This increase is mainly because of two reasons; one is the increase in the price of fossil fuel and second is the need to reduce emissions. Thus, wind power is very favorable as it has no fuel input. It gives wind producers a big chance to participate in electricity markets. However, bidding wind energy in short-term electricity markets has high associated risks due to the uncertainties in hourly available wind, energy prices, and imbalance penalties. Therefore, wind producer must hedge against this uncertainty to be effectively profitable. One of the solutions is developing a balancing mechanism that allows covering the lack of production caused by uncertain sources such as wind energy. Combined cycle units are good resources that achieve this balancing mechanism as they have high efficiency and several distinguished characteristics that make it a competitive participant in the electricity market [10].

1.3 THESIS OBJECTIVES

This research aims to develop a balancing mechanism for wind energy thereby making it a competitive source in electricity markets. This mechanism is represented by coordinating bidding of wind energy with combined cycle source. Stochastic programming will be applied. The thesis objectives can be outlined as follows:

1- To develop a stochastic model of bidding from combined cycle unit participating in electricity markets.
2- To develop a coordinated bidding strategy for wind energy and combined cycle units.
3- To compare the coordinated bidding with the uncoordinated bidding in the electricity market.
4- To study the influence of risk control by using the conditional value at risk (CVaR) on the coordinated case.

1.4 THESIS ORGANIZATION

This thesis is organized as follows:

Chapter 1 introduces the thesis work, and gives a brief description of various important terminologies. The thesis motivation and research objectives are stated.

Chapter 2 presents a detailed literature survey on energy market, trading wind energy and how to deal with their risks. Concepts of combined cycle unit and their model types are also studied. The benefits of coordinated wind and simple cycle unit are described. Finally, a survey on stochastic programming is enclosed.

Chapter 3 describes the important components of system under study. A coordinated wind and combined cycle units constitute the system model. Trading energy in electricity market is discussed. Detailed modeling of combined cycle unit is also presented. Generation & reduction of scenarios is carried out through stochastic programming approach.

Chapter 4 presents stochastic programming based mathematical formulation of the proposed system. The main objective of maximizing profits is derived by considering constraints for combined cycle and wind units. The conditional value at risk is also added to the objective function.

In Chapter 5 test system that shows the input data and framework program model is presented. In addition, the risk-neutral results and the influence of adding conditional value at risk to main objective function are discussed.

Chapter 6 concludes this research work and gives some directions for the possible future work.

CHAPTER2 LITERATURE SURVEY

This chapter presents a detailed literature survey on the energy trading from wind and combined cycle units.

2.1 ENERGY MARKET

Generally, many countries in the world are moving towards a deregulated environment for electricity market instead of the traditional centralized approach. The main objective of electricity market is to decrease the cost of electricity and to improve operational efficiency. In general, there are two types of deregulated markets: pool-based market and bilateral contract-based market [14],[15]. Each has its own mechanism for long-term and short-term energy sales.

2.2 WIND ENERGY

Globally, the wind power is steadily penetrating into the power systems due to its free availability with zero emissions [2]. Many of the wind producers are paid feed-in tariffs for their production or a minimum price to secure them against the price fluctuations of electricity markets.

However, in other market, wind producers are penalized if they deviate from their schedule. Hence, wind power forecast becomes important. A consequence, the challenge is how a wind producer should bid in the pool markets to achieve maximum profit while controlling the variability and uncertainty factors.

Researchers have developed three approaches to deal with risks associated with the variability and uncertainty of bidding wind energy [7]. The first approach is based on coordinated trading of wind power and other sources of energy (such as pump-storage, hydro and thermal etc.) [4]-[8],[16],[17]. The second one develops a tool of financial options to mitigate wind producers from the wind risks [18]. The last approach introduces a stochastic model to produce optimal strategies for wind producers participating in electricity market [19]-[20].

2.3 COMBINED CYCLE UNITS

2.3.1 Combined Cycle Unit Description

Combined Cycle Units are widely installed in several countries around the world. CCUs are expected to reach 28% of total U.S power system by 2018 [21]. This increase in the installation of combined cycle units is due to their distinct advantages such as high efficiency, faster response, shorter installation time, abundance of gas, lower capital cost, and eco-friendly compared with a thermal simple cycle unit [9],[15],[22]-[23]. These features of CCUs are corresponding with aspirations of electricity market and hence they give the CCUs a big opportunity to be one of the competitive generating sources [24],[25],[26].

Typically, a combined cycle unit consist of one or more combustion turbines (CTs), each with heat recovery steam generator (HRSG) and one or more steam turbine (ST), as shown in Figure 2.1. The steam produced in the HRSGs is used to drive a steam turbine. Each CT/ST has an electrical generator that produces electric power [27],[28],[29].

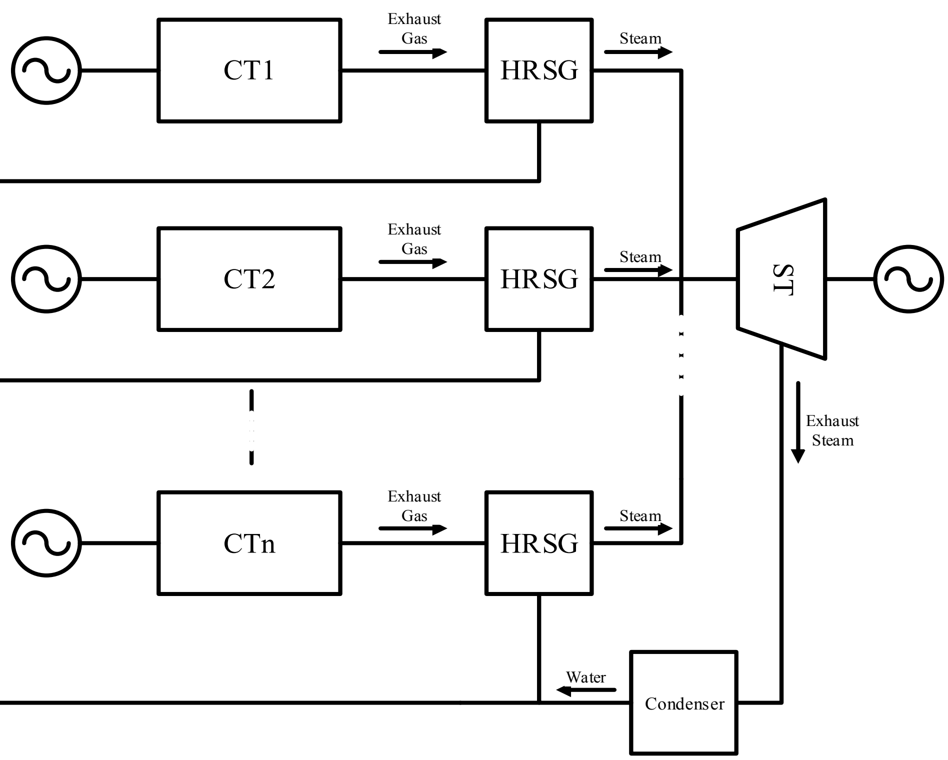

Figure 2.1 Combined Cycle Plant

2.3.2 Modeling Techniques of Combined Cycle Units

The researchers discussed three approaches for modeling combined cycle units: the aggregated model, configuration–based (mode) model, and physical unit–based (component) model.

A- Aggregated model

This model is the simplest model where all components of combined cycle unit is aggregated in one unit and treated as a thermal unit. The unit commitment schedule of CCU is independent on configurations and their constraints. Aggregated model is used in NYISO, MISO and PJM [30].

B- Mode model

This model depends on combinations of combustion turbines and steam turbines. Each combination represents a configuration or a mode. Each mode is considered as a pseudo unit. These pseudo units have their own operating constraints, such as startup cost, minimum up/down time, and so on. The transition of the model corresponds to the operating rules of each mode and their constraints [31],[9] and [32].

C- Component model

In this model, each CT and ST is treated as a pseudo unit that has its own operating constraints. The transitions state of the model is based on the configurations of the combination and a group of constraints. The advantages of this model compared with the previous model are as follows [29]:

1- It is more accurate because it reflects the reality of CCU by representing each CT and ST as a separate unit.
2- It enforces lower operating cost for CCU.

3- It requires less number of variables and constraints for mixed integer linear programming formulation.

However, the component model is complex when used for optimization problem due to its dependency on the state transition among each component. Consequently, component variables are very tight. More detail on the component model and a comparison between mode model and component model is presented in [29].

2.3.3 Solution Methodologies for Unit Commitment with CCUs

Various techniques have been developed by researchers to solve the unit commitment and security constraint (SUC) with combined cycle units. In [31], the authors used lagrangian relaxation (LR) method to schedule the unit by decomposing the problem into a set of single problems. Each single problem is then solved by Dynamic Program (DP). The configuration based mode is used to model the CCU. In addition, a variable "mod" is defined for each configuration taking two values called dependent mode and called exclusive mod.

The work in [9] describes short term scheduling of CCUs to determine the optimal unit commitment when security constraints are included. The problem is decomposed into a master problem (unit commitment problem) and a slave problem (SUC problem) by using LR and DP techniques. The problem is divided into a set of individual sub-problems. Based on the mode model for CCU and state space diagram, DP is used to solve unit commitment of each sub-problem during the sort-term. Further explanation of state space diagram based mode model is as follows:

The authors built the state space diagram for CCU corresponding to the operational rules of each mode and the connection between the modes. For example, for a combined cycle unit with two CTs and one ST, Table 2.1 shows the possible modes for CCU. Figure 2.2 and Figure 2.3 represent the state transitions between the modes; upward transition diagram and downward transition diagram, respectively based on the rules below:

1- Neglecting the state transition between the same modes.
2- The combination consisting of several CTs can be turned ON/OFF simultaneously. However, the combination consisting of CT and ST cannot turned ON/OFF simultaneously.
3- The changes in the number of CTs and STs for each mode affect on the transition cost between the modes.

Table 2.1 Modes of Combined Cycle Unit

Mode	**Component**
0	(0CT+0ST) OFF
1	(1CT+0ST)
2	(2CT+0ST)
3	(1CT+1ST)
4	(2CT+1ST)

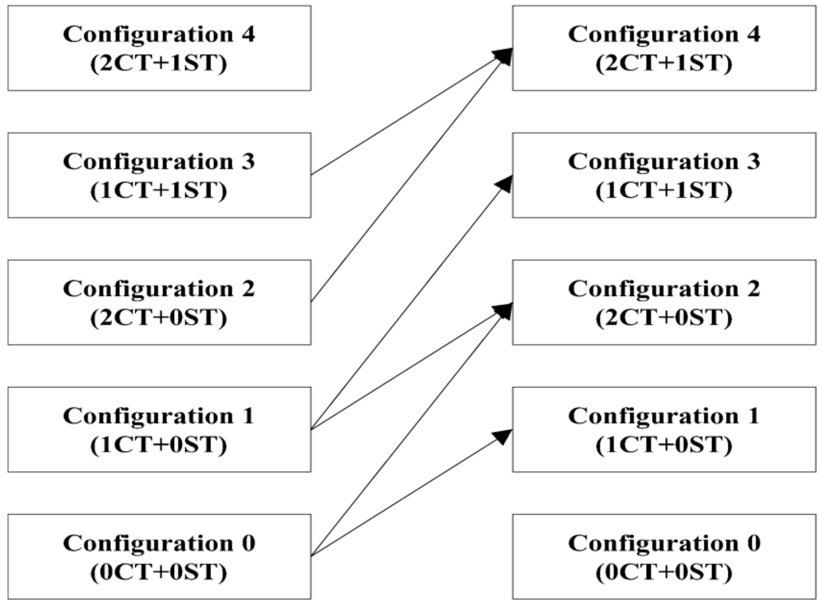

Figure 2.2 Upward state-transition diagram[9]

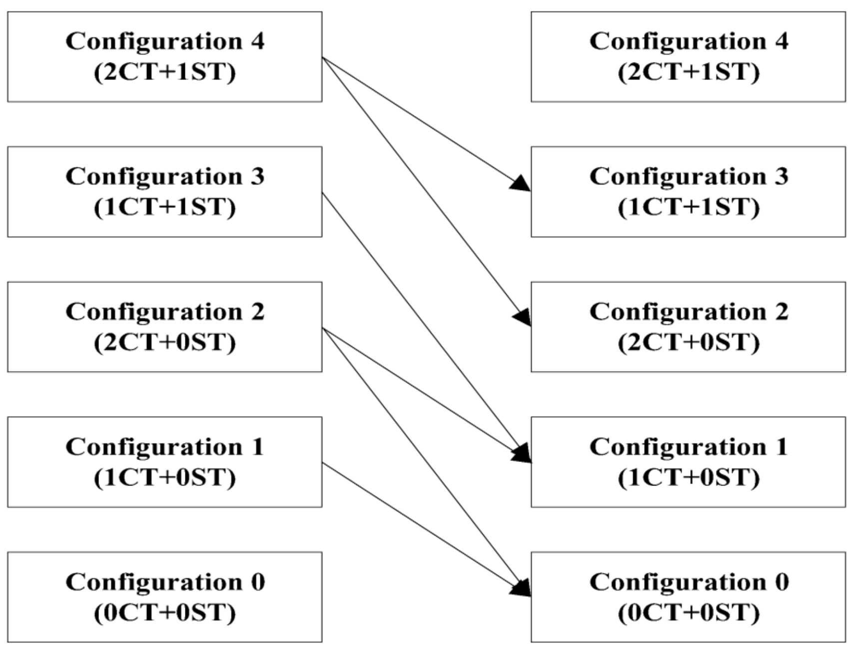

Figure 2.3 Downward state-transition diagram[9]

In [32], security constrain problem with CCU is solved by dynamic program. CCU is configuration based where each configuration is a pseudo unit. LR technique and Bender's decomposition are also used. Based on the operation of flexible units, the whole model expanded to three types; combined cycle units, mixed fuel units and dual fuel units. The objective is to obtain the unit commitment of the whole unit while minimizing the violations in the network.

In [29], modeling combined cycle unit as a component model has been presented. The combined cycle component (CCC) model is represented by CTs and STs as individual components. Also, comparison between combined cycle mode model and component model is presented. The unit commitment problem of component model is then solved by applying mixed integer linear programming (MILP). The objective function was minimizing the total operating cost while satisfying the demand.

Most of the various approaches to model combined cycle are summarized in literature of paper [33]. The two different modeling approaches: configuration-based modeling and physical unit modeling are carried out to ensure the system reliability. Mixed integer programming (MIP) technique is used on configuration based combined cycle to solve unit commitment (UC) of a day head market (DAM) and physical model is applied for real-time market Security Constrained Economic Dispatch (SCED).

Unit commitment for CCU is obtained using dual programming [34]. Combined cycle unit modeling is based on component model where each component is treated as a pseudo unit and has its own characteristics such as such as startup cost, minimum up/down time. Dynamic Program under dual optimization is used to schedule each sub-problem unit. Modeling of hybrid combined cycle unit is developed in this study by using an auxiliary boiler to improve the production of steam turbine.

Finally, in [35], a mixed integer linear programming technique is used to obtain the optimal schedule of combined cycle unit during short-term. Configuration based model is considered and its state space diagram is represented. Two CTs and one ST constitute a CCU. The system reserve is included as a constraint and also some operating constraints (startup and minimum up/down time) are taken in to account.

2.3.4 Combined Cycle Units in Markets

Participating combined cycle units in a market depends on the rules of that specific market. For example:

In ERCOT Nodal Market

In [33], based on the modeling combined cycle unit , ERCOT nodal market offers two different ways for CCU participation as well as including security constraint as follows:

- Mode - based approach, each mode in combined cycle unit is considered as a separate source in optimization scheme. It has its own operating parameters, power output and constraints and it offers bidding curves to the market.
- Component mode approach is used in SUC analysis and in Market Management System (MMS). Each component in CCU is a separate unit. It is

suitable for power flow, network analysis and protection scheme since it is more accurate.

In 2010, Nodal Protocol requirements are reviewed by ERCOT and it submitted new Nodal Protocol Revision Request (NPRR) to include CCUs. Two main definitions of CCU in NPRR are represented as follows:

- Combined Cycle Train (CCT): are the integrations of CT and ST in a generating unit that uses more than one thermodynamic cycle. The combinations are listed as a unit in ERCOT CCT where it can operate in one or more configurations of CCU.
- Combined cycle generation resource (CCGR): is a particular mode of physical generation source (CT and ST) with its own parameters and constraints listed in CCT with ERCOT.

However, the Iberian market deals with combined cycle unit as traditional thermal unit [36].

2.4 COORDINATION BENEFITS

As reported in [8], coordination of wind power with conventional single cycle sources (thermal units) is helpful for wind producers owing to the distinguished characteristics of a thermal unit. The thermal unit is predictable and controllable compared with wind power. When sharing these two sources in a pool market, there is a period time between the real-time and the time of wind producers submitting their production. This gap leaves wind producers very susceptible to imbalances penalties.

In addition, wind-thermal coordination, especially at periods of thermal low profitability (due to thermal constraints such as minimum up/down times and minimum power outputs) is beneficial for both wind and thermal units. Compared to conventional thermal units, combined cycle unis (CCUs) have higher efficiency, faster response (i.e. CCU could demonstrate operating at lower operation cost) and more environmental friendliness [9],[15],[22]-[23]. Therefore, the coordination of wind power with CCUs is expected to be very beneficial, especially to balance the wind mismatch.

2.5 STOCHASTIC PROGRAMMING

The coordination of the CCU and wind power is a complex optimization problem due to the uncertainties and stochastic nature of the types of power plant. Stochastic programming deals with the problems of making optimal decisions under uncertainty [11]-[13],[36],[37]. All of these works talked about the stochastic programming as methodology technique, especially on wind energy producer's problem. However, none of the previous works applied this technique to CCU scheduling. One of the most comprehensive works which considered the uncertainty in wind producers is found in [8]. This work deals with the coordinated bidding of wind power and single cycle unit, formulated using mixed-integer stochastic programming. The uncertainties in optimization are handled through two-stage decision-making process. The first-stage is called “here-and-now” and must be done before the stochastic variables are realized. The second stage is called “wait-and-see” and it is influenced by the decisions taken in the first stage. The second stage is finished when the stochastic variables are realized.

CHAPTER3 SYSTEM DESCRIPTION

This chapter describes energy trading, the important concepts of combined cycle unit used in research and the procedure to apply stochastic technique for the system.

3.1 TRADING IN POOL MARKET ENERGY

This thesis is based on the short-term pool-based Iberian electricity market. The Iberian market deals with combined cycle units as conventional thermal units. Each of the power producers submits bids for each hour.

Thus, the Iberian market looks only at the amount of energy each GENCO would produce and its price [36]. In this market, energy prices are set as follows:

- At a certain time of each day (10:00 A.M.), producers and consumers bid hourly prices and quantities, respectively, for the next day.
- The market clearing process is carried out by the Independent System Operator (ISO) to determine the market clearing price (MCP) and cleared quantity for each producer and each hour.
- The final clearing price is adjusted in several intra-day periods until the total energy generated equals the total energy consumed (balancing market).

Energy imbalances, i.e. the differences between the real time generation and the cleared quantities, are penalized depending on the rules of penalty. For instant, the Iberian market, the rule of penalty of imbalances depends on the behavior of imbalances for the supply with respect to the whole system. Thus, for a power producer, if the generation is less than demand, a penalty is imposed on those suppliers and vice versa. Consequently, we can divide imbalances penalty to under generation and over generation penalty as detailed in [8].

3.2 COMBINED CYCLE UNIT

A simple combined cycle unit is represented by one combustion turbine and one steam turbine. Its operation begins by burning a mixture of air and natural gas in combustion chamber. The released energy by the combustion is used to drive the CT, which lead to moving the rotor of generator to produce the electricity. Then the waste heat from a gas turbine is used by HRSG to generate steam and this steam is used to drive the ST which in turn drives a steam generator to produce electricity.

In most CCUs, the flexibility of the unit is reflected by configuring the combustion turbine and steam turbine to operate in several modes. For instance, Figure 3.1 shows a combined cycle unit consisting of two CTs and one ST. This unit can operate in five individual modes. Note that mode 1 transits to either mode 2 or 3 before its transition to mode 4. The steam turbine cannot operate alone. Thus, increasing the number of component (CT/ST) increases the complexity of state diagram [29].

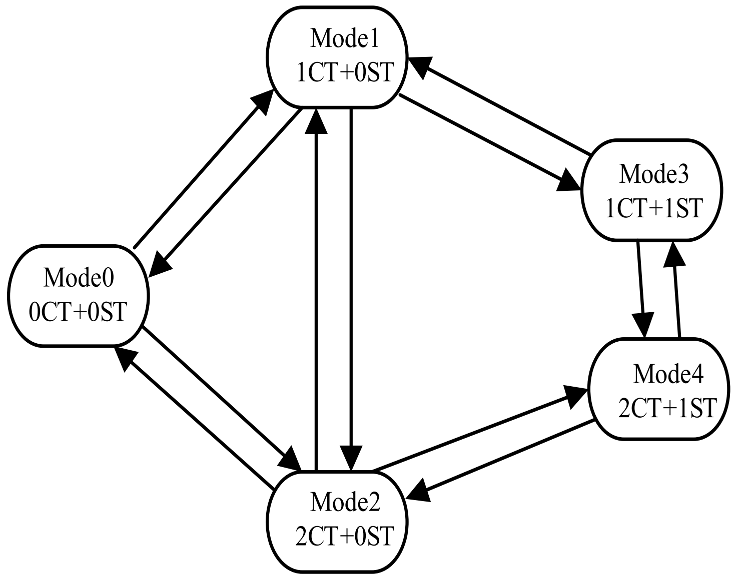

Figure 3.1 State transition diagram for CCGT (2CT+1ST)

The study is based on combined cycle component model because the component model is more accurate than mode model for the modeling of CCUs. And, the number of variables and constraints for MIP formulation are less than in the mode model [29]. In this model, each combustion turbine and each steam turbine is regarded as a separate unit with its own unit parameters and generation characteristics, such as ramping rate limits, minimum on/off time limits, and startup/shutdown costs.

3.3 STOCHASTIC PROGRAMMING TECHNIQUE

This work is based on two-stage stochastic programming (SP). Each uncertain parameter is expressed as a finite set of realization, called scenarios [38]. As discussed in [8], [39], there are two different types of decision variables in two-stage SP:

1) Variables that are independent of scenarios and they are decided upon in “here-and-now” stage, such as hourly bids of the wind plants and combined cycle unit and the combined cycle unit commitment schedules.
2) Variables that are dependent of the realized scenarios and are determined in “wait-and-see” stage, such as the combined cycle unit’s actual power outputs (as they depend on the realized scenarios of wind power), energy prices, and imbalance prices.

Thus, scenarios should be generated in SP so as to build the scenario tree for the uncertainties.

3.3.1 Scenario Generation

There are several technique to generate scenarios of each stochastic variable [11], [13], [36], [40], [41]. In this thesis, Seasonal Auto Regressive Integrated Moving Average (S-ARIMA) technique is used to generate scenarios for energy market prices and imbalance penalties that represents seasonal characteristic appropriately as described in [7]. In addition, a development methodology technique used to generate scenarios for wind power as found in [8] is used. This method is based on:

a) Hourly wind power that gives the wind forecasts and follows the normal distribution. And, also provides wind forecast associated with mean and standard deviations during day-ahead market.
b) The ramping rate of the wind power following the normal distribution should be known from the historical data.

Thousands of scenarios are generated for all uncertainties parameters (stochastic variables). Consequently, the problem will become computationally intractable. Thus, the number of scenarios should be reduced until the problem become tractable.

3.3.2 Scenario Reduction

One of the most commonly used technique used in stochastic optimization problem to reduce number of scenarios is called the Kantorovich distance, generally found in [39],[42][43]. In this thesis, a forward selection algorithm used as reported in [8],[42]. This method is appropriate to the electricity market problem and also it maintains the substantial properties of the original scenario tree. It can be explained as follows:

1) Start with empty sub set; choose scenario from the original set that minimizes distance between reduced and original set in each iteration.
2) Put the scenario selected in the empty set and delete it from the original after iteration.
3) Continue until an identified number of scenarios is selected and the probability of set of reduced scenarios selection is determined.

This method is applied on all the uncertainty variables: wind power output, energy market price and imbalances penalty.

CHAPTER4 STOCHASTIC PROGRAMMING BASED BIDDING FORMULATION

This chapter presents the mathematical detail for coordinated trading of combined cycle and wind units based on stochastic programming.

4.1 OBJECTIVE FUNCTION

The main objective function is to maximize the expected profit of a GENCO that owns combined cycle and wind plants. The objective function is as follows:

$$\underset{\left(i_{tj}, I_{tk}, w_{tsd}, p_{tsu}, p_{tsu}^{ac}\right)}{Maximize} \; E\,[PROFITS] \tag{4.1}$$

The three terms in (4.2) represent the per-scenario profits due to the combined cycle plant, wind plants and imbalances, respectively.

$$E\,[PROFITS] = \sum_{s=1}^{N_s} \pi_s \,.\, [PFCC_s + PFW_s + PFIMB_s] \tag{4.2}$$

The per-scenario profits of CCU can be expressed as:

$$PFCC_s = \sum_{u=CC} \sum_{t=1}^{NT} \rho_{ts} P_{tsu} - \sum_{j\epsilon CT} \sum_{t=1}^{NT} F_c . \left[\sum_{j\epsilon CT} F_{f_{tsj}} + \sum_{j\epsilon CT} SU_{f_j} . y_{jt} + \sum_{j\epsilon CT} SD_{f_j} . z_{jt}\right] \tag{4.3}$$

Equation (4.3) includes the combined cycle unit's energy revenues, combined cycle unit's production cost, the startup cost and shutdown cost per period and per generating unit.

The profit from the wind plant can be shown as:

$$PFW_s = \sum_{t=1}^{N_T} \sum_{d=1}^{N_D} \rho_{ts} \,.\, W_{tsd} \quad ,\forall\, s \tag{4.4}$$

The imbalances profit term consists of the imbalance-up profit and the imbalance-down penalty. This can be integrated for under-generation and over-generation penalty multipliers in one stochastic variable [8] and can be expressed as follows:

$$PFIMB_s = \sum_{t=1}^{N_T} [\rho_{ts}^{o}.\, \rho_{ts}.\, ImbUp_{ts} - \rho_{ts}^{u}.\, \rho_{ts}.\, ImbDn_{ts}\,] \quad ,\forall\, s \tag{4.5}$$

4.2 COMBINED CYCLE UNIT CONSTRAINTS

Several combined cycle constraints are included in this study. They are formulated as follows:

4.2.1 Piecewise-Linearized Cost Function

A combined cycle unit consists of a combination of one combustion turbine and one steam turbine. Each CT has a fuel-MW curve and MW-generated steam. Each ST has a consumed steam-MW curve as shown in Figure 4.1.

Equations (4.6)-(4.8) represent the piecewise linearization of the (fuel consumption-MW) curve of combustion turbine (CT).

$$F_{f_{tsj}} = \sum_{j\epsilon CT}\left[F_{f_j}^0 . i_{tj} + \sum_{e=1}^{N_E}\left(IF_{f_{ej}} . \delta_{etsj}\right)\right] \quad (4.6)$$

$$P_{tsj}^{ac} = P_{min,j} . i_{tj} + \sum_{e=1}^{N_E} \delta_{etsj} \quad ,\forall\, t, s, j \quad (4.7)$$

$$0 \leq \delta_{etsj} \leq BrkPt_{ej} - BrkPt_{e-1,j} \quad ,\forall\, e, t, s, j \quad (4.8)$$

where $F_{f_j}^0 = a_j + b_j . P_{min,j} + c_j . P_{min,j}^2$

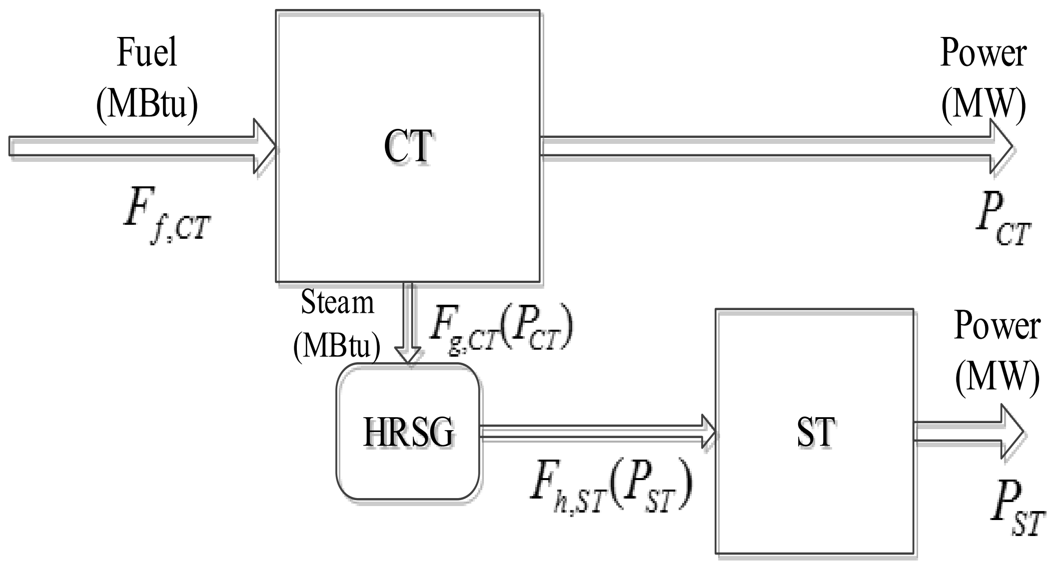

Figure 4.1 CC Component Model with 1CT and 1 ST.

The MW-consumed piecewise curve can be expressed as:

$$F_{g_{tsj}} = \sum_{j\epsilon CT}\left[F_{g_j}^0 . i_{tj} + \sum_{e=1}^{N_E}\left(IF_{g_{ej}} . \delta_{etsj}\right)\right] \quad (4.9)$$

where $F_{g_j}^0 = a_j + b_j . P_{min,j} + c_j . P_{min,j}^2$.

$$F_{h_{tsk}} = \sum_{k\epsilon ST}\left[F_{h_k}^0 . I_{tk} + \sum_{e=1}^{N_E}\left(IF_{h_{ek}} . \delta_{etsk}\right)\right] \quad (4.10)$$

$$P_{tsk}^{ac} = P_{min,k} . I_{tk} + \sum_{e=1}^{N_E} \delta_{etsk} \quad ,\forall\, t, s, k \quad (4.11)$$

$$0 \leq \delta_{etsk} \leq BrkPt_{ek} - BrkPt_{e-1,k} \ ,\forall\, e,t,s,k \tag{4.12}$$

Equations (4.10), (4.11) and (4.12) represent the piecewise linearization for the steam consumed-MW curve of the steam turbine.

where $F_{h_k}^0 = a_k + b_k.P_{min,k} + c_k.P_{min,k}^2$.

4.2.2 The Relationship among Unit Status, Startup and Shutdown Indicators

Equations (4.13) - (4.15) represent the status of CT and the relation between the status and the startup and shutdown. Similar equations can also be written for ST.

$$j.\left(i_{tj} - 1\right) = \sum_{j\epsilon CT} i_{tj} \ ,\forall\, t,j \tag{4.13}$$

$$y_{jt} = max\left(0, i_{tj} - i_{(t-1),j}\right) \ ,\forall\, t,j \tag{4.14}$$

$$z_{jt} = max\left(0, i_{(t-1),j} - i_{tj}\right) \ ,\forall\, t,j \tag{4.15}$$

4.2.3 Steam Coupling Constraint

Equation (4.16) represents the heat exchange between CT-HRSG and steam turbine. Note that the cost of steam consumed by ST is not included in the objective function as no additional fuel is needed for producing steam.

$$\sum_{k\epsilon ST} F_{h_{tsk}} + HL \leq \sum_{j\epsilon CT} F_{g_{tsj}} \tag{4.16}$$

4.2.4 Combined Cycle Operating Term Constraints

Actual output power and bidding output power for each component (CT/ST) can be demonstrated within the limits, respectively as follows:

$$i_{tj}.P_{min,j} \le P_{tsj}^{ac} \le P_{max,j}.i_{tj} \quad ,\forall\, t,s,j \tag{4.17}$$

$$I_{tk}.P_{min,k} \le P_{tsk}^{ac} \le P_{max,k}.I_{tk} \quad ,\forall\, t,s,k \tag{4.18}$$

$$i_{tj}.P_{min,j} \le P_{tsj} \le P_{max,j}.i_{tj} \quad ,\forall\, t,s,j \tag{4.19}$$

$$I_{tk}.P_{min,k} \le P_{tsk} \le P_{max,k}.I_{tk} \quad ,\forall\, t,s,k \tag{4.20}$$

$$P_{tsu}^{ac} = \sum_{j\epsilon CT} P_{tsj}^{ac} + P_{tsk}^{ac} \quad ,\forall\, t,s,j,k,u \tag{4.21}$$

$$P_{tsu} = \sum_{j\epsilon CT} P_{tsj} + P_{tsk} \quad ,\forall\, t,s,j,k,u \tag{4.22}$$

Equation (4.21) shows the total actual output power of combined cycle unit (CTs and ST) and equation (4.22) represents the total bidding output power for combined cycle unit. Ramping up/down limits are enforced as (4.23) for CT and (4.24) for ST.

$$-RD_j \le P_{(t+1),s,j} - P_{tsj} \le RU_j \quad ,\forall\, t,s,j \tag{4.23}$$

$$-RD_k \le P_{(t+1),s,k} - P_{tsk} \le RU_k \quad ,\forall\, t,s,k \tag{4.24}$$

Minimum up and down time for each combustion turbine and steam turbine can be modeled similarly.

$$\sum_{t=1}^{UT}\left(1 - i_{tj}\right) = 0 \quad ,\forall\, t,j \tag{4.25}$$

$$\sum_{n=t}^{t+T_{min,j}^{up}-1} i_{nj} \ge T_{min,j}^{up}.y_{tj} \qquad ,\forall\, j, t = UT_j + 1 \dots . NT - T_{min,j}^{up} + 1 \tag{4.26}$$

$$\sum_{n=1}^{NT}\left(i_{nj} - y_{tj}\right) \ge 0 \qquad ,\forall\, j, t = NT - T_{min,j}^{up} + 2 \dots . NT \tag{4.27}$$

Equations (4.25), (4.26) and (4.27) represent the minimum up time of CT for each scenario where$UT_j = max\{0, min[NT, (T_{min,j}^{up} - X_{ini,j}^{on}).i_{j,0}]\}$.

Minimum down time of CT in each scenario can be expressed as follows:

$$\sum_{t=1}^{DT} i_{tj} = 0 \quad ,\forall\, t,j \tag{4.28}$$

$$\sum_{n=t}^{t+T_{min,j}^{down}-1} \left(1 - i_{nj}\right) \geq T_{min,j}^{down}.\, z_{tj} \qquad ,\forall\, j,t = DT_j + 1 \ldots NT - T_{min,j}^{down} + 1 \tag{4.29}$$

$$\sum_{n=1}^{NT} \left(\left(1 - i_{nj}\right) - y_{tj}\right) \geq 0 \qquad ,\forall\, j,t = NT - T_{min,j}^{down} + 2 \ldots .NT \tag{4.30}$$

where $DT_j = max\{0, min[NT, (T_{min,j}^{down} - X_{ini,j}^{off}).\, i_{j,0}]\}$.

4.2.5 Transition and State coupling Constraints

The transition between different modes of CCU is expressed as a set of simple constraints. Thus, one type of CCUs is considered in this work, where CCS1 represents the set of CCUs with multiple CTs and one ST (n CT- 1 ST) as reported in [29]. Relations (4.31) – (4.34) have been employed to model the CCS1 formulations.

$$\sum_{j \epsilon CT} y_{tj} \leq NCTN1^{su}.\, (1 - Y_{tk} - Z_{tk}) + NCTN2^{su}.\, Y_{tk} + NCTN3^{su}.\, Z_{tk} \quad ,\forall\, t,k \tag{4.31}$$

Equation (4.31) represents the maximum number of CTs that can be started up simultaneously.

$$\sum_{j \epsilon CT} z_{tj} \leq NCTN1^{sd}.\, (1 - Y_{tk} - Z_{tk}) + NCTN2^{sd}.\, Y_{tk} + NCTN3^{sd}.\, Z_{tk} \quad ,\forall\, t,k \tag{4.32}$$

Equation (4.32) represents the maximum number of CTs that can be shut down simultaneously.

$$\sum_{j\epsilon CT} i_{tj} \geq nCTN1^{on}.\left[\sum_{k\epsilon ST} I_{tk} - NST + 1\right] \quad ,\forall\, t \tag{4.33}$$

Equation (4.33) represents the minimum number of CTs that must be on for running all STs.

$$\sum_{j\epsilon CT} i_{tj} \leq NCTN1^{on} + NCT.\sum_{k\epsilon ST} I_{tk} \quad ,\forall\, t \tag{4.34}$$

Equation (4.34) represents the number of CTs that can be on without operating any STs.

$$\sum_{n,j\epsilon CT} i_{nj} \geq Y_{tk}.nCTN2^{on} \qquad ,\forall\, t, k = 1, n = t - nCTT^{on}, \dots, t-1 \tag{4.35}$$

Equation (4.35) represents the required number of CTs that must be on for a minimum number of hours before starting the first ST.

4.3 NON-DECREASING BIDDING CURVES AND WIND OPERATING CONSTRAINTS

Relations (4.36) - (4.39) have been employed to achieve non-decreasing bidding curves with respect to spot energy price for combined cycle and wind units, respectively.

$$(\rho_{ts} - \rho_{ts'})(P_{ts} - P_{ts'u}) \geq 0 \qquad ,\forall\, t, s, s', u \tag{4.36}$$

$$if(\rho_{ts} - \rho_{ts'}) = 0, (P_{ts} - P_{ts'u}) = 0 \qquad ,\forall\, t, s, s', u \tag{4.37}$$

$$(\rho_{ts} - \rho_{ts'})(W_{tsd} - W_{ts'd}) \geq 0 \qquad ,\forall\, t, s, s', d \tag{4.38}$$

$$if(\rho_{ts} - \rho_{ts'}) = 0, (W_{tsd} - W_{ts'd}) = 0 \quad ,\forall\, t, s, s', d \tag{4.39}$$

where s' represents scenario and $s' < s$.

The output power bidding for each wind plant should be within the limits as shown in equation (4.40), wherein the actual power during day a head is forecasted for each scenario and each period.

$$0 \leq W_{tsd} \leq \bar{W}_d \qquad ,\forall\, t, s, d \tag{4.40}$$

4.4 ENERGY IMBALANCE CONSTRAINTS

The energy imbalances as described previously in literature and in objective function; are the differences between the real time generation and the cleared quantities. The imbalances are divided to: imbalance up; if the difference is negative and imbalance down; if the difference is positive.

$$ImbDn_{ts} - ImbUp_{ts} = W_{tsd} - W_{std}^{ac} + \sum_{j\epsilon CT}\left(P_{tsj} - P_{tsj}^{ac}\right) + \left(P_{tsk} - P_{tsk}^{ac}\right) \qquad ,\forall\, t, s \tag{4.41}$$

$$0 \leq ImbUp_{ts} \leq W_{std}^{ac} + \sum_{j\epsilon CT} P_{tsj}^{ac} + P_{tsk}^{ac} \qquad ,\forall\, t, s \tag{4.42}$$

$$0 \leq ImbDn_{ts} \leq \bar{W}_d + \sum_{j\epsilon CT} P_{max,j}.\, i_{tj} + \sum_{k\epsilon ST} P_{max,j}\,.\, I_{tk} \qquad ,\forall\, t, s \tag{4.43}$$

Equations (4.41) - (4.43) are employed to model the imbalance constraints for coordinated combined cycle and wind units.

4.5 RISK CONTROL INCORPORATION

In this work we employ control risk metric called Conditional Value at Risk (CVaR). It represents the expected profit of the least profitable scenarios as reported in [8]. CVaR can be included linearly in our problem and hence it is used [44]. The conditional value at risk with 95% confidence level is incorporated into the main objective function [7], [8]. The resultant is shown under:

$$\underset{\left(i_{tj}, I_{tk}, w_{tsd}, p_{tsu}, p_{tsu}^{ac}, \xi, \eta_s\right)}{Maximize} E\left[PROFITS\right] + \beta . CVaR_{\alpha} \tag{4.44}$$

where

$$CVaR_{\alpha} = \xi - \frac{1}{1-\alpha} \sum_{s}^{N_s} \pi_s . \eta_s \tag{4.45}$$

$$\xi - \eta_s - \left[PFCC_s + PFW_s + PFIMB_s\right] \le 0 \qquad ,\forall s \tag{4.46}$$

$$\eta_s \ge 0 \qquad ,\forall s \tag{4.47}$$

In (4.44), β is a version-risk parameter and the equations (4.46) and (4.47) have been employed as a constraint for risk control.

CHAPTER5 TEST SYSTEM AND SIMULATION RESULTS ANALYSIS

This chapter presents the test system and simulation results for system under study. Risk-neutral and risk-aversion test cases are studied.

5.1 INPUT DATA OF THE SYSTEM

In this system, a producer who owns one wind plant and one CCU, both connected to the same point of interconnection is considered. The producer participates in the Iberian day-ahead energy market. The capacity for the wind plant is 400 MW. The combined cycle unit consists of four combustion turbines and one steam turbine. The input-output quadratic coefficients for each component are given in Table 5.1.

Table 5.1 QUADRATIC COEFFICIENTS OF CCU COMPONENTS

component	$(I/O) Curves$	a $(Mbtu/h)$	b $(Mbtu/Mwh)$	c $(Mbtu/ Mw^2h)$
CT1	fuel-MW	160.13	55.5	0.035
	MW-Steam	50.13	25.5	0.015
CT2	fuel-MW	55.23	40.2	0.015
	MW-Steam	32	23	0.0215
CT3	fuel-MW	151.08	50.37	0.023
	Mw-Steam	65.03	23.12	0.018
CT4	fuel-MW	70.08	50.37	0.023
	MW-Steam	65.03	23.12	0.018
ST	Steam-MW	63.13	48.5	0.035

Each quadratic function is piecewise linearized using ten segments. Table 5.2 and

Table 5.3 show the operating characteristics and the parameters for transition coupling constraints of the combined cycle unit, respectively.

Table 5.2 OPERATING CHARACTRISTICS OF CCU COMPONENTS

	CT1	**CT2**	**CT3**	**CT4**	**ST**
P_{min}	5	10	15	25	20
P_{max}	55	90	65	125	170
T_{min}^{up}	1	3	1	3	3
T_{min}^{down}	1	3	1	3	3
RU	35	80	50	100	150
RD	35	80	50	100	150
SU	10	80	70	40	-
UT	0	0	0	0	0
DT	0	0	0	0	0

Table 5.3 PARAMETERS FOR TRANSITION COUPLING CONSTRAINTS

$NCT1^{su}$	2	$NCT1^{on}$	2
$NCT2^{su}, NCT3^{su}$	0	$nCT1^{on}$	2
$NCT1^{sd}$	2	$nCT2^{on}$	2
$NCT2^{sd}, NCT3^{sd}$	0	$nCTT^{on}$	2

The number of scenarios depends on the number of uncertain variables. As a consequence, 125 scenarios are employed by forecasting five values for each of the three uncertain variables (wind power output, spot market energy price and imbalance up/down price). The values of the uncertain variables are taken from [8]. For instance, Figure 5.1 and Figure 5.2 represent five scenarios for wind actual output power and another five scenarios for spot market energy price, respectively.

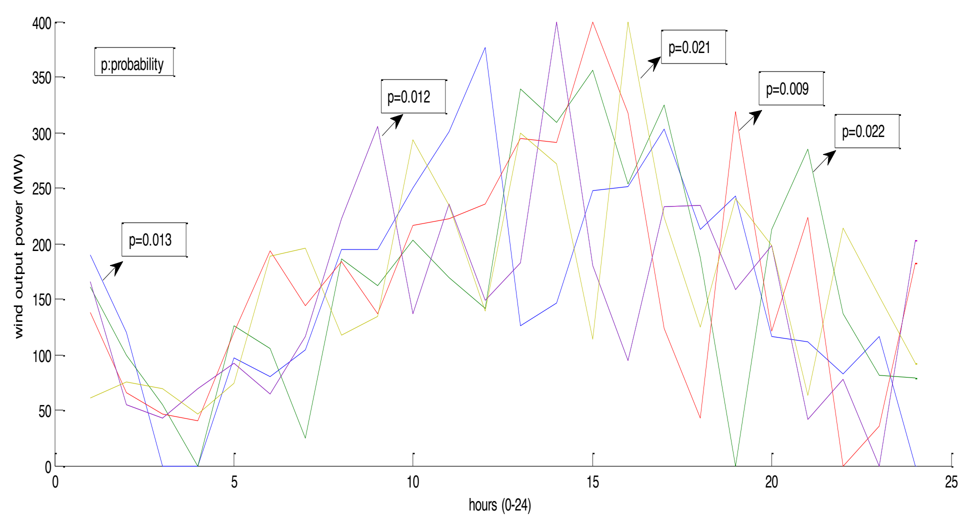

Figure 5.1 Scenarios for Wind Output Power Range

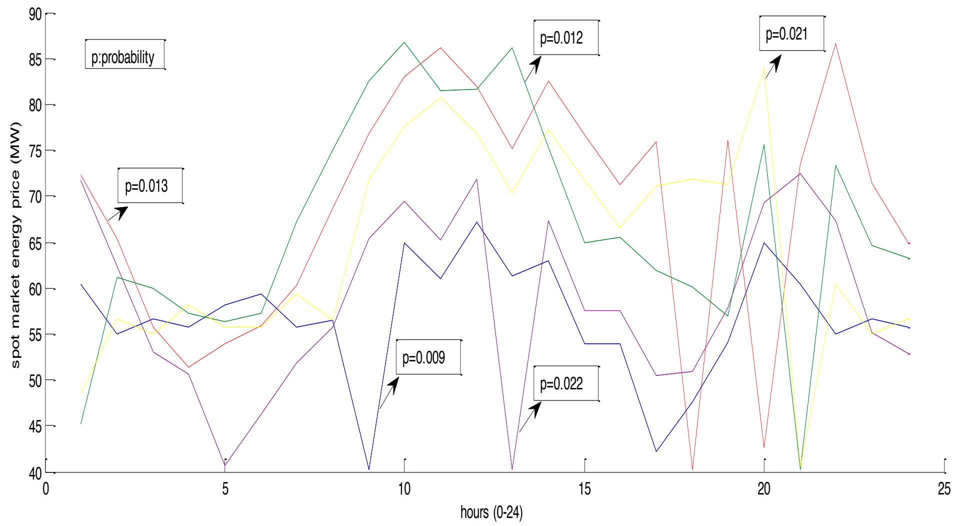

Figure 5.2 Scenarios for Spot Market Energy Price

The simulation system has been implemented in CPLEX 12.4 (IBM product for optimization language) [45] and using high performance computing (HPC) with two Intel(R) Xeon(R) processors (2 GHz. each) and 40 GB RAM memory. The range of running times is about 25 minutes in the uncoordinated case and 59 minutes in the coordinated case with incorporating risk control. The simulation system has been run several times for various values of a version-risk parameter (β) in order to compare the results of risk-neutral and risk-aversion for coordinated and uncoordinated bidding cases.

5.2 RISK NEUTRAL RESULTS

This case is carried out by setting β=0 in the optimization for uncoordinated combined cycle, uncoordinated wind, and coordinated combined cycle-wind bidding strategies, respectively. Table 5.4 shows the comparison on the expected profits of each case and coordinated gain is as high as 0.3%. The unit commitment of uncoordinated and coordinated cases is shown in Table 5.5 and Table 5.6, respectively. It can be seen from Table 5.6, coordination results with CT1 more committed (i.e. having digit 1 in bold) since CT1 is the most flexible component in the combined cycle unit.

Table 5.4 EXPECTED PROFIT OF RISK-NEUTRAL COORDINATED VS UNCOORDINATED BIDDING STRATEGIES

Case	Expected Profits
Uncoordinated CCU (€)	145,150
Uncoordinated wind (€)	138,710
Sum of Uncoordinated wind and CCU (€)	283,860
Coordinated wind-CCU (€)	284,700
Coordination Gain (€)	840
Coordination Gain (%)	**0.3**

Table 5.5 COMMITMENT SCHEDUAL FOR UNCOORDINATED CCU, $\beta = 0$

Unit	**Hours (0-24)**
CT1	0111111111111000000011111
CT2	0111111111111111111111111
CT3	0000000001111110000010000
CT4	0000000001111111111110000
ST	0111111111111111111111111

Table 5.6 COMMITMENT SCHEDULE FOR COORDINATED CCU, $\beta = 0$

Unit	**Hours (0-24)**
CT1	011111111111**11**0000011111
CT2	0111111111111111111111111
CT3	0000000001111110000010000
CT4	0000000001111111111110000
ST	0111111111111111111111111

Different bidding curves for various bidding hours (9, 13, 18 and 20) of combined cycle and wind, for the uncoordinated and coordinated cases are shown in Figures 5.3-5.6, respectively. For hours 9, 18 and 20, there is a change in bid volumes due to coordination although there is no change in unit commitment schedule for the CCU, see Tables 5.5 and 5.6.

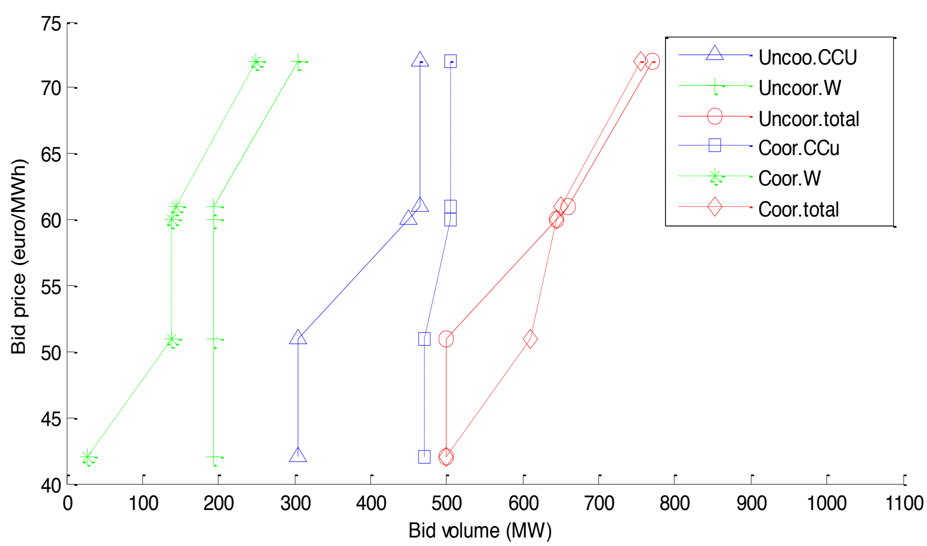

Figure 5.3 Bidding Curves for Hour 9, $\beta = 0$

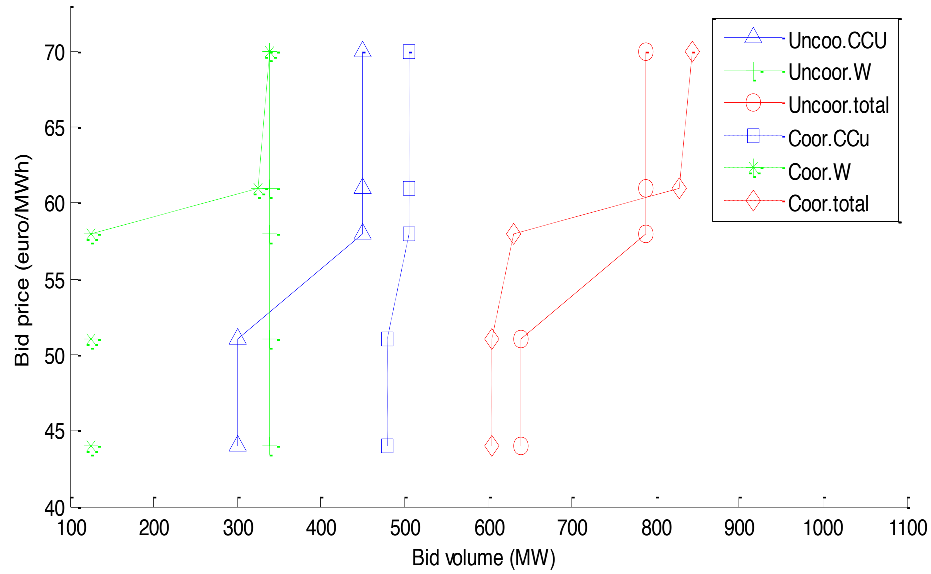

Figure 5.4 Bidding Curves for Hour 13, β = 0

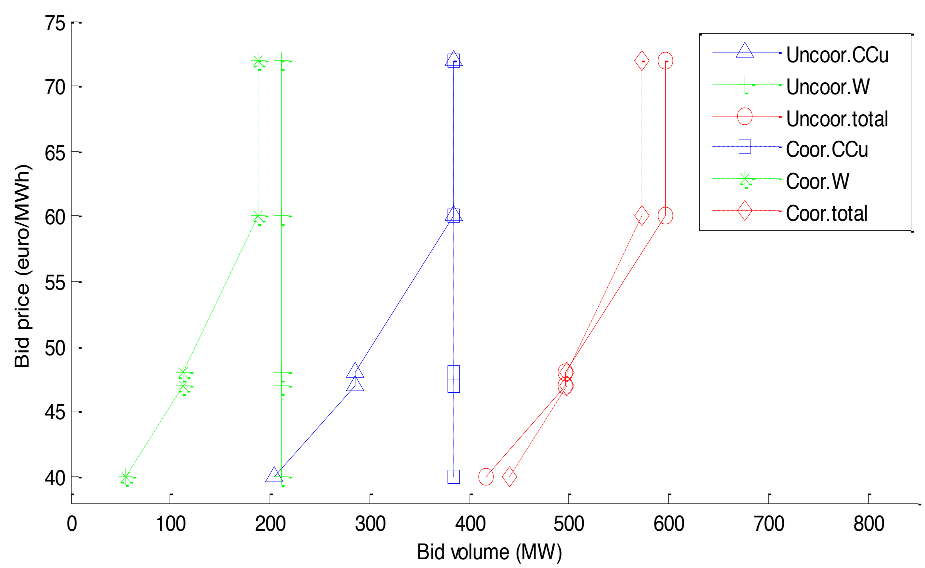

Figure 5.5 Bidding curves for hour 18, $\beta = 0$

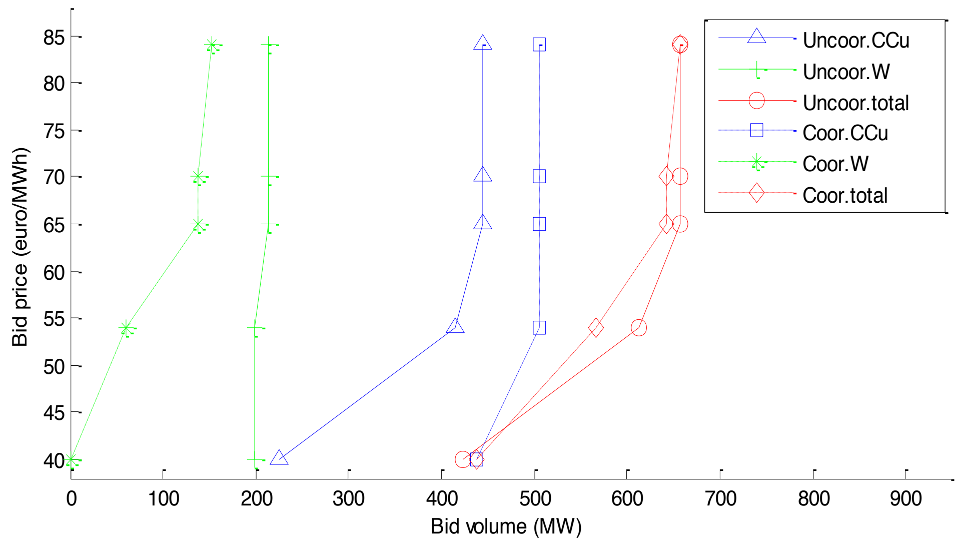

Figure 5.6 Bidding curves for hour 20, $\beta = 0$

5.3 THE INFLUENCE OF RISK CONTROL

This case is carried out with β>0 (i.e. for different values of β) to study the influence of the conditional value at risk on the coordinated and uncoordinated cases for both CCU and wind unit. For β = 0.1, the simulation studies is carried out to compare the unit commitment schedule of uncoordinated and coordinated CCU for risk-aversion and risk-neutral bidding strategies. The unit commitment of uncoordinated CCU is shown in Table 5.7. The results in Table 5.7 show that the units are decommitted more often when compared with uncoordinated CCU in Table 5.5. This is due to an improvement in the conditional value at risk when the CCU tends to avoid the lowest profitable scenarios.

In addition, the comparison between unit commitments of uncoordinated CCU (with risk and without risk) with the unit commitment of coordinated case (with risk) shows that the coordinated case is committed more. The balance in the wind mismatch is observed for coordinated operation when the CCU is more committed. This can be found in Table 5.5, Table 5.7 and Table 5.8.

Table 5.7 COMMITMENT SCHEDULE FOR UNCOORDINATED CCU, $\beta = 0.1$

Unit	**Hours (0-24)**
CT1	011111111**0000**0000000**0**1111
CT2	0111111111111111111111111
CT3	000000000**000000**0000010000
CT4	0000000001111111111110000
ST	0111111111111111111111111

Table 5.8 COMMITMENT SCHEDUAL FOR COORDINATED CCU, β = 0.1

Unit	**Hours (0-24)**
CT1	0111111110000000000001111
CT2	0111111111111111111111111
CT3	0000000000111000000010000
CT4	0000000001111111111110000
ST	0111111111111111111111111

The effect of the conditional value at risk (β = 0.1) on the optimal bidding curves of CCU and wind for uncoordinated and coordinated cases is shown in Figures 5.7-5.10. Here it can be observed that coordinated combined cycle bid volumes have changed considerably.

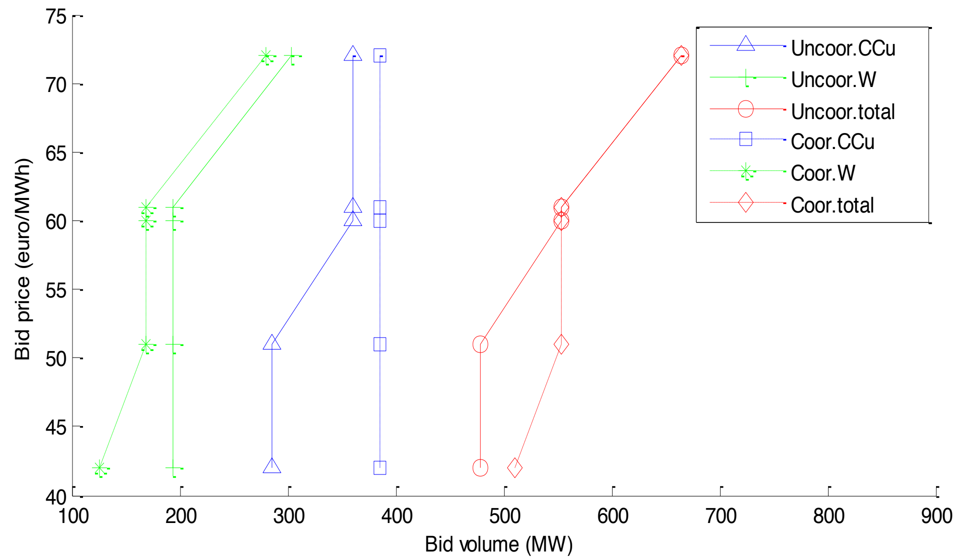

Figure 5.7 Bidding Curves for Hour 9, $\beta = 0.1$

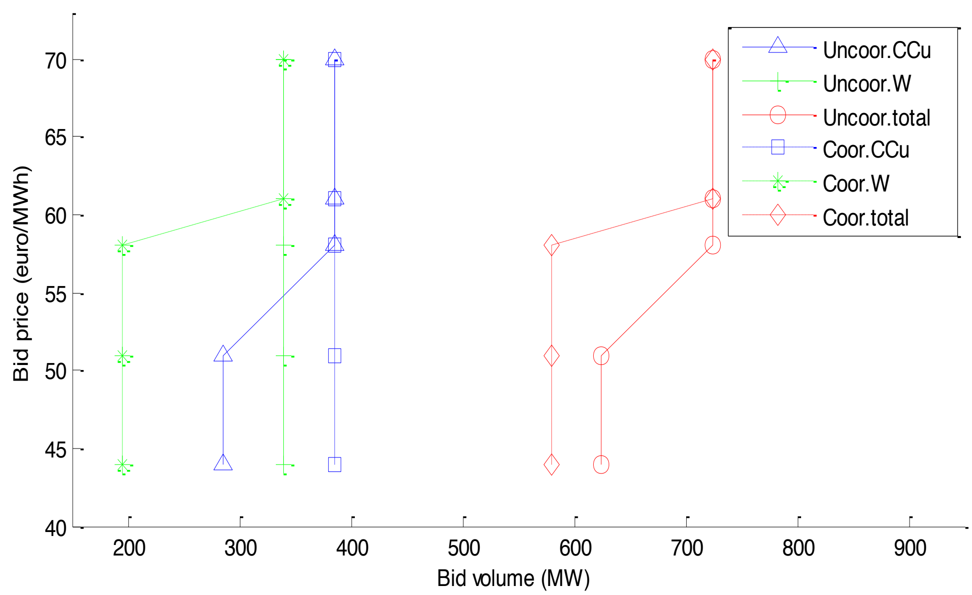

Figure 5.8 Bidding Curves for Hour 13, $\beta = 0.1$

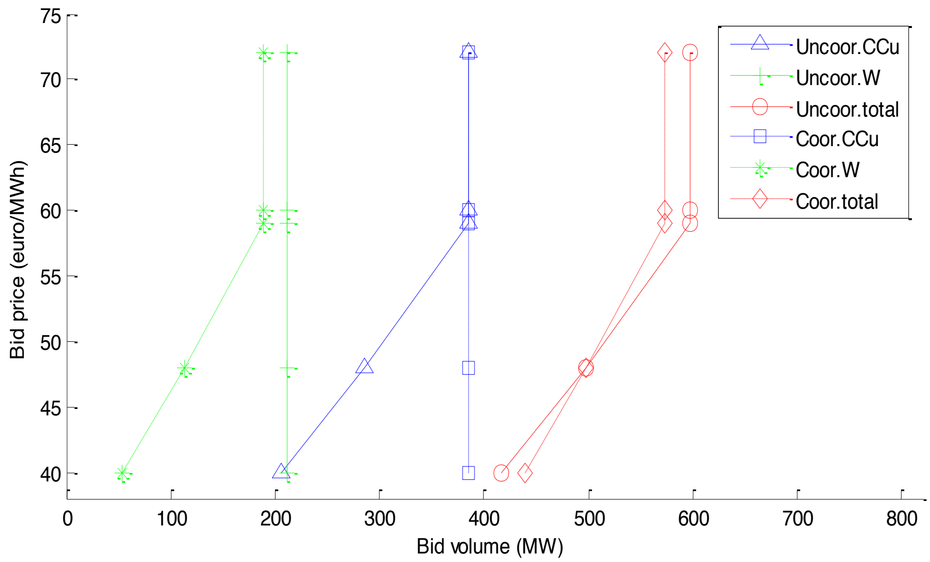

Figure 5.9 Bidding Curves for Hour 18, $\beta = 0.1$.

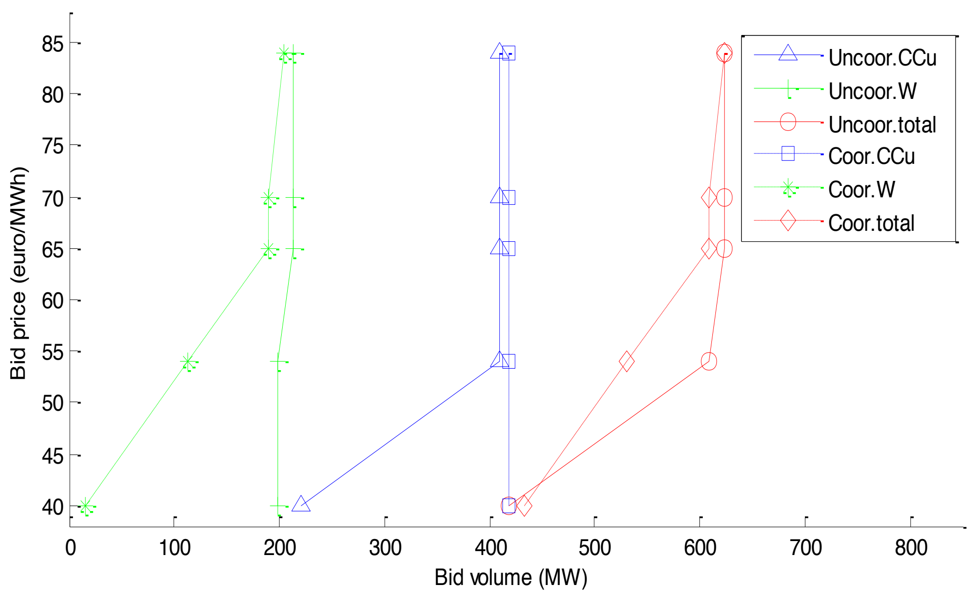

Figure 5.10 Bidding Curves for Hour 20, $\beta = 0.1$.

In order to study the influence of risk control on bidding curves, different bid volumes with β = 0.1 and β = 0 for uncoordinated and coordinated cases of CCU and wind are shown in Figure 5.11 and Figure 5.12. These figures depict that the risk-neutral bids are always greater than or equal to the risk-aversion bids. This is because in risk-aversion case, the wind unit tends to reduce its bids and CCU tends to decommit more units to avoid risky bidding.

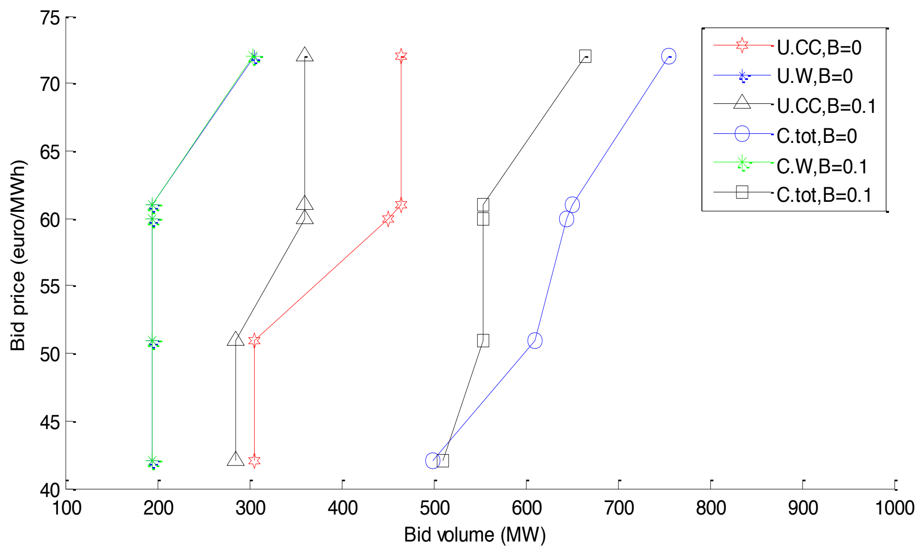

Figure 5.11 Bidding Curves for Hour 9, $\beta = 0$ & $\beta = 0.1$

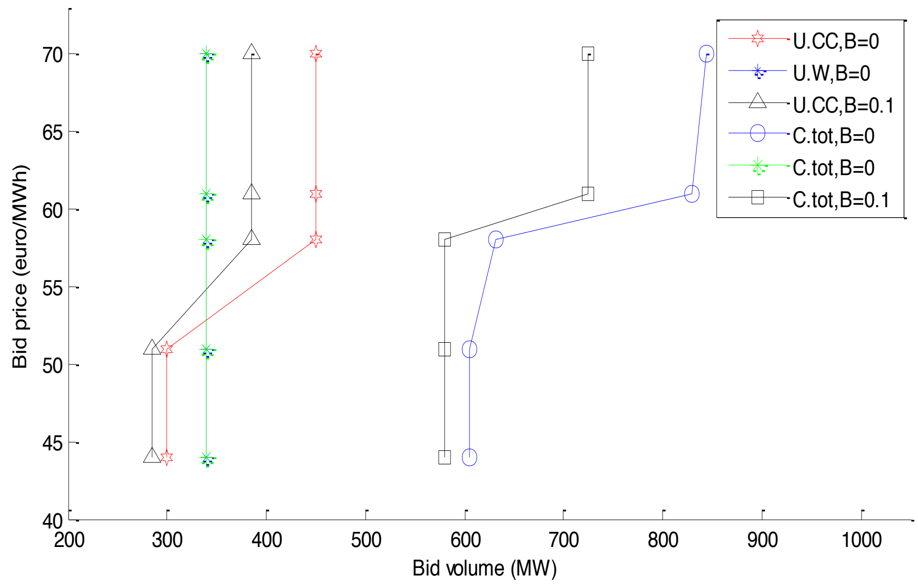

Figure 5.12 Bidding Curves for Hour 13, $\beta = 0$ & $\beta = 0.1$

Table 5.9 shows the expected profits and conditional value at risk for different values of β for coordinated combined cycle and wind units. As expected, this table indicates that when β increases, the expected profits drop and CVaR increases.

Table 5.9 EXPECTED PROFITS & CVaR FOR SEVERAL β

	Coordinated(CCU & W)	
β	Profit	CVaR
0	284700	68452
0.1	284460	77247
0.3	283770	82266
0.5	283050	83992
0.7	281020	87505
0.9	281020	87505
1.1	281020	87512
1.3	281000	87524
1.5	281000	87524

More specific cases showing the impact of risk aversion can be observed in Table 5.10 and Figure 5.13. These also show the expected profits and CVaR for several values of β, for individual wind and individual combined cycle bidding strategies, respectively. From Table 5.10 it is seen that for individual wind bid, when β increases from 0 to 1.7, the CVaR increases by 9% and expected profit reduce by only about 0.2%. Also, for individual combined cycle bid, when β increases from 0 to 1.7, the CVaR increases by more than 60% and the expected profit reduces by only 2% as shown in Figure 5.13.

Table 5.10 EXPECTED PROFITS & CVaR FOR UNCOORDINATED WIND BIDDING

	Uncoordinated Wind(W)	
β	Profit	CVaR
0	138710	46438
0.1	138700	49900
0.3	138620	50296
0.5	138610	50332
0.7	138610	50332
0.9	138600	50334
1.1	138590	50352
1.3	138500	50422
1.5	138490	50431
1.7	138480	50433

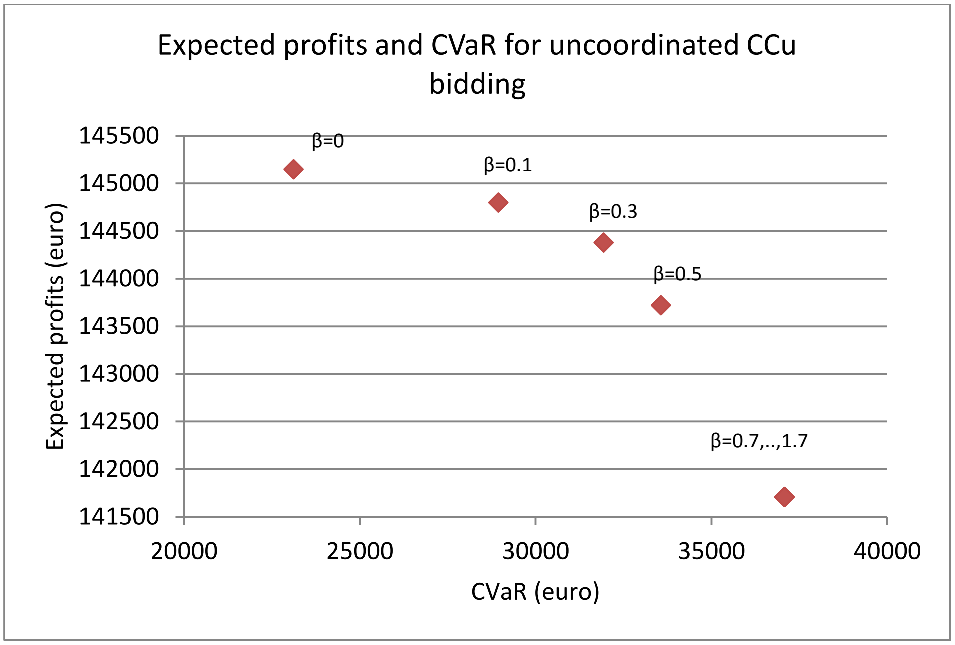

Figure 5.13 Expected profits and CVaR for uncoordinated CCU bidding

Figure 5.14 shows the comparison of expected profits and CVaR for the sum of uncoordinated bids and coordinated bids for different values of β. It indicates that few points among the coordinated case are higher and generally lie to the right of the sum of uncoordinated case.

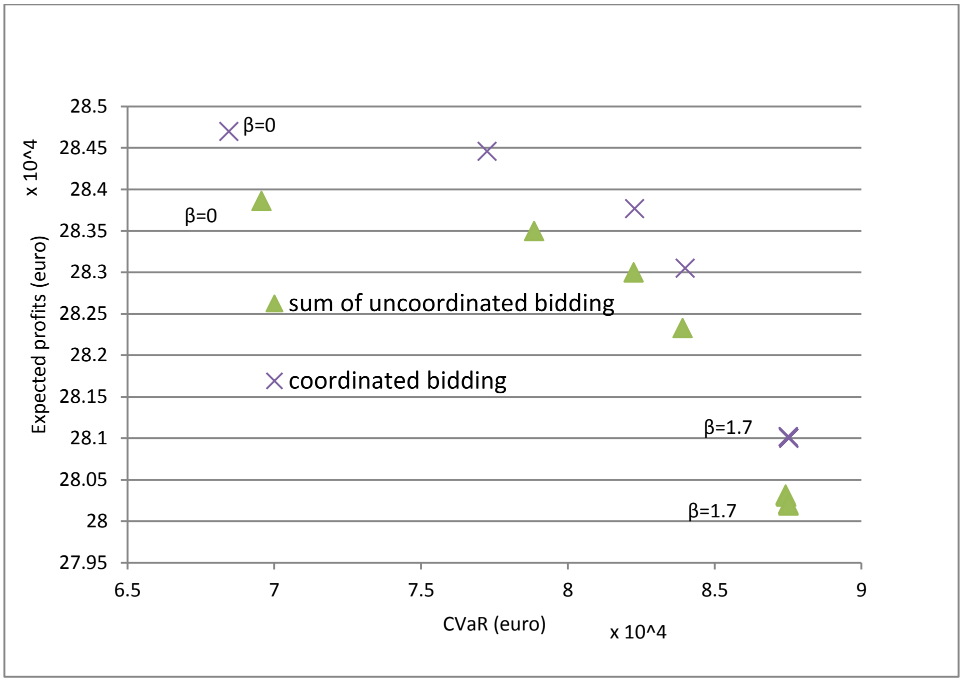

Figure 5.14 Expected Profits and CVaR for Sum of Uncoordinated & Coordinating Bidding

CHAPTER6 CONCLUSION AND FUTURE WORK

6.1 CONCLUSION

In this thesis a stochastic model of bidding for a combined cycle unit participating in electricity market has been developed. Various constraints for a combined cycle unit such as minimum up/down time, ramping rates, minimum and maximum power outputs, and startup costs are taken in to consideration. Also, a coordinated bidding strategy for combined cycle and wind energy units has been developed. Maximizing the expected profit is the objective function while mitigating the high risks associated with bidding of wind energy in short-term energy market. Stochastic programming (SP) is used in order to represent uncertainties associated with wind power output, spot market energy price, and imbalance up/down price.

The results show that;

1) The CCU-wind coordination increases the expected profit.
2) For a coordinated CCU with more committed units balance in the wind mismatch is enhanced.

The risk-neutral bids are always greater than or equal risk-aversion bids because the wind unit tends to reduce its bids and CCU tends to decommit more in risk-aversion.

6.2 FUTURE WORK

The following subjects are recommended for future work.

a. The above research involving a stochastic model of bidding for a coordinated combined cycle & wind units participating in short-term electricity markets can also be extended to long-term markets.
b. By adding some ancillary services to the model participation in regulation market is possible.
c. A comparative study between a stochastic model and a deterministic model can be carried for long-term markets to estimate the benefits of coordination.

NOMENCLATURE AND SYMBOLS

t	Bidding period
s	Scenario
u	Combined cycle unit
j	Combustion turbine
k	Steam turbine
d	Wind pant
e	Segment
P_{tsu}	Total optimal bid of combined cycle unit
P_{tsj}	Optimal bid of combustion turbine
P_{tsk}	Optimal bid of steam turbine
W_{tsd}	Optimal bid of wind plant
P_{tsu}^{ac}	Total actual power output from combined cycle unit
P_{tsj}^{ac}	Actual power output from combustion turbin
P_{tsk}^{ac}	Actual power output from steam turbine

i	Combustion turbine state; 1 means ON; 0 means OFF
I	Steam turbine state; 1 means ON; 0 means OFF
y	Binary indicator for startup of combustion turbine
Y	Binary indicator for startup of steam turbine
z	Binary indicator for shutdown of combustion turbine
Z	Binary indicator for shutdown of steam turbine
δ_{etsj}	Combustion turbine power output for each segment of piecewise linear (Fuel-MW) curve.
δ_{etsk}	Steam turbine power output for each segment of piecewise linear (Consumed steam-MW) curve.
f, g, h	Fuel-MW curve, MW-generated steam curve, and consumed steam-MW curve, respectively.
F_f	Combustion turbine; fuel consumption (MBtu)
F_g	Combustion turbine; steam generated (MBtu)

F_h	Steam turbine: steam consumed (MBtu)
HL	Heat load (MBtu)
$ImbUp_{ts}$	Total over-generated energy in excess of combined schedule
$ImbDp_{ts}$	Total under-generated energy in deficit of combined schedule
$PFCC_s$	Total combined cycle unit profits for each scenario
PFW_s	Wind profits for each scenario
$PFIMB_s$	Imbalances profits for each scenario
$PROFITS$	Total expected profits
ζ *and* η	Auxiliary variables for computing CVaR
W_{tsd}^{ac}	Actual power output from wind plant
ρ^u, ρ^o	Under- and over-generation imbalance penalties as multipliers of the energy price.
ρ_{ts}	Spot market energy price
$CVaR\alpha$	Conditional value at risk at the confidence interval
α	Confidence level

B Risk-aversion parameter

π_s Probability of a scenario

SU, SD Startup and shutdown fuels of a component, respectively

UT, DT Initial minimum up/down time for a component, respectively

$T_{min}^{up}, T_{min}^{down}$ Minimum up time and minimum down time for a component, respectively.

RU, RD Ramping up and ramping down of a component, respectively (MW/h).

F^0 Offset of a piecewise linear for f, g and h input-output curves (MBtu).

IF Slope of a segment in a piecewise linear for input/output curves (MBtu/MWh).

$BrkPt$ Break point of segment of the piecewise linear for a component.

P_{min}, P_{max} Power output limits of a component, (MW).

$NCT1^{su}$ Maximum number of CTs that can be started up simultaneously for a CCU when its ST is kept on previous status, started up, or shut down respectively from 1 to 3.

$NCT1^{sd}$ Maximum number of CTs that can be shut down simultaneously for a CCU when its ST is kept on previous status, started up, or shut down respectively from 1 to 3.

$nCT1^{on}$ Minimum number of online CTs for a CCU to operate all STs.

$nCT2^{on}$ Minimum number of online CTs for a CCU to start the first ST.

$NCT1^{on}$ Maximum number of online CTs for a CCU when all STs are off.

$nCTT^{on}$ Minimum number of hours the CTs of a CCU must have been on before operating an ST.

$X_{ini}^{on}, X_{ini}^{of}$ Number of hours a component has been initially on or off.

NT Number of periods for scheduling unit

F_c Fuel cost (€/MBtu).

ACRONYMS AND ABBREVIATIONS

CCU	Combined Cycle Unit
CCGTs	Combined Cycle Gas Turbines
CTs	Combustion Turbines
ST	Steam Turbine
MILP	Mixed Integer Linear Programming
SP	Stochastic Programming
CVaR	Conditional Value at Risk
GENCOs	Generation Companies
HRSG	Heat Recovery Steam Generator
CCC	Combined Cycle Component
UC	Unit Commitment
DAM	Day Ahead Market
ERCOT	Electric Reliability Council of Texas
SCED	Security Constrained Economic Dispatch

ISO	Independent System Operator
MCP	Market Clearing Price
S-ARIMA	Seasonal Auto Regressive Integrated Moving Average

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